Quantum-Boltzmann-Machine Neuron Device

Nan-Jian Wu, Naoto Shibata¹ and Yoshihito Amemiya

Faculty of Engineering, Hokkaido University, Sapporo, Japan Phone: +81-11-706-6080, Fax: +81-11-706-7890 E-mail:nanjian@sapiens.huee.hokudai.ac.jp ¹Dai Nippon Printing Co.,Ltd. Tokyo, Japan

1. Introduction

One of the challenges in microelectronics is to develop new functional devices that utilize quantum mechanical effects. Because electrons in a quantum mesoscopic structure show probabilistic behavior, such a device could produce stochastic operations naturally. Hence a quantum device would be suitable for neural networks that utilize probabilistic architectures for processing. This paper proposes for the first time a Boltzmann-machine neuron device that uses quantumcoupled single electrons.

The Boltzmann machine (BM) is a kind of feedback neural network based on a stochastic architecture. It can solve various problems such as combinatorial optimization, association and pattern recognition.^{1,2)} But, it is difficult to construct BM LSIs by using ordinary devices because it requires many controllable noise sources for the stochastic operation that consist of an enormous number of devices.³⁾

To solve this problem, we propose a novel BM neuron device that uses quantum-coupled single electrons - what we call a quantum-Boltzmann-machine (QBM) neuron device. In the following sections we will give the device structure, and analyze its operation, and demonstrate that the device can perform stochastic operations of the BM device.

2. QBM neuron device

Figure 1 shows the schematic structure of the proposed QBM device. It consists of a two-dimensional arrangement of coupled-quantum dots. Each quantum dot is occupied by an electron. The electron shows two spin polarizations "up" and "down". If we define the polarizations "up" and "down" of the single-electron spin as logic states 1 and 0, the single-electron spins can be used to encode binary information.⁴⁾ The operation of the neuron device is as follows. Each input signal is transmitted through an input line to an input dot.



Fig. 1. Schematic structure of the QBM device. It consists of a two-dimensional arrangement of quantum dots. The circles represent the quantum dots.

The states of the input dots drive the state of the operating dot, and then the operating dot determines the state of the output dot. The output is transmitted through the output line to other neurons. Each input is weighted by the exchange interaction coefficient J_i . The polarization of the electron spin at the operating dot is given stochastically due to thermal agitation. Thus the QBM generates an output of 1 with the probability P,

$$P = \frac{1}{1 + exp(U/K_{\rm B}T)} , \quad U = -4\sum_{i}^{n} J_{i}S_{i}$$
(1)

where $K_{\rm B}$ is the Boltzmann constant, T is the temperature, $S_{\rm i}$ is the polarization of the spin at the i-th input dot, and U is the local field.

3. Operation of QBM neuron device

We only take the interaction between the nearestneighbor quantum dots into account and neglect the interaction between the next nearest-neighbor quantum dots. We simulated the operation of the QBM neuron device by using the Metropolis Monte Carlo method and the Ising model, 5)

$$H_{\text{Ising}} = -2\sum_{k=i} J_{kj} S_k S_j \tag{2}$$

where S_k and S_j are spin polarizations $(\pm 1/2)$ of the electrons at the k and j quantum dots. The exchange interaction coefficient between the spins of the electrons at k and j quantum dots is J_{kj} .

We first calculated the strength J_{kj} of the electron interaction between the spins of the electrons at neighboring coupled-quantum dots using the Hubbard model. The



Fig. 2. Energy levels of the low-energy ferromagnetic and antiferromagnetic states as a function of the overlap integral in a two-quantum-dot system.

ground state of the two-electron system corresponds to the antiferromagnetic state, as shown in Fig. 2. The strength J_{kj} of the electron interaction is negative and decreases as the overlap integral increases.

We then simulated the operation of a linear array of quantum dots using the Metropolis Monte Carlo method. Figure 3 shows a typical development of the system energy of the array for an input spin of 1/2. To make the input line transmit the polarization of the spin, the exchange interaction coefficient J between the nearest-neighbor spins in the input line was designed to be much larger than J_i between the operating dot and the input dot. Initially, we gave an arrangement of the parallel electron spins in the quantum dot array with higher energy. The spin system eventually reached a stable state, which is antiferromagnetic. This means that the information of the spin 1/2 was transmitted correctly from the input dot to the output dot.



Fig. 3. A typical development of the system energy of a 11-dot linear array for an input 1 (spin "up") with Monte Carlo simulation time.



Fig. 4. Outputs of the QBM device for average values of the inputs: a) average value is 0.32, and b) average value is 0.68. The neuron device has 25 inputs



Fig. 5. Probability of the output 1 of the QBM as a function of average value of 25 inputs for various temperature. All of the strength of the interaction between the operating dot and the input lines are considered to be the same values J_s .

Finally, we calculated the whole operation of the QBM by using the Metropolis Monte Carlo method. Figure 4 shows the outputs for two average input values. We can see that the probability for output 1 can be controlled by the inputs. Figure 5 shows the calculated probability of output 1 of the QBM device as a function of the inputs for various temperatures. For simplicity, all of the strengths of the interaction between the operating dot and the input lines are considered to be the same value as J_s . The probability shows a typical sigmoid characteristic. At high temperatures, the neuron device gives the outputs of 0 and 1 with a probability of approximately 0.5. When the temperature is lowered, if the local field U is much larger (or smaller) than 0, the neuron device gives almost an output of 1 (or 0). This demonstrates that the device can perform the stochastic operations of the BM neuron.

4. Conclusions

We proposed for the first time a Boltzmann-machine neuron device that uses quantum-coupled single electrons. It consists of a two-dimensional arrangement of quantum dots that are occupied by single conduction-band electrons. The two possible polarizations "down" and "up" of the electron spin are used to encode the two states 0 and 1 of the BM neuron. The simulation results demonstrate that the neuron device can perform stochastic operation of the BM neuron.

References

- M. Akazawa and Y. Amemiya, Appl. Phys. Lett., 70 (1997) 670.
- G. E. Hinton and T. J. Sejnowski, in Parallel Distributed Processing' Explorations in the Microstructure of Cognition, edited by D. E. Rumlhart et al. (Cambridge, 1986) P. 282.
- 3. Y. Aima et al., IEEE J. Solid-State Circuits, 26, 1637(1991).
- 4. S. Bandyopadhyay et al., Nanotechnology, 5 (1994) 113.
- 5. J. H. Jefferson et al., Phys. Rew., B54 (1996) 4903.